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Greening the Heat Investigating the Impact of Vegetative Roofs on Thermal Regulation in Buildings

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Abstract

Climate and its protection, use of renewable energy sources, global warming, etc. As for the projection of buildings, this is nowadays the most watched aspect in the creation of the concept of each of them. Whether it is a new building or a reconstruction. Various subsidy aspects are set up for this issue. In general, we know subsidies for the renewal of buildings in the form of a subsidy for insulation. It is also possible to obtain a subsidy for resources, either in the form of a heat pump or photovoltaic panels. For apartment buildings, renovations are adapted in so-called packages or combinations. All this should serve to reduce the need for energy for heating as well as electricity. This work is rather passive in how this need can be reduced.

Keywords: renewable energy sources, passive heating, vegetative roof

1 Introduction

1.1 Optimizing Building Energy Performance

In the contemporary world, the energy efficiency of buildings holds paramount importance, wielding a profound influence on both energy consumption and environmental sustainability. The imperative to enhance energy efficiency is a linchpin in curbing our carbon footprint and addressing the urgent challenges of climate change.

Global warming remains a persistent and critical concern, garnering frequent attention from media outlets, while public awareness of its ramifications continues to grow. The far-reaching consequences of climate change manifest in altered weather patterns, exerting a substantial impact on the global populace. Urbanization emerges as a primary catalyst for these transformations [1], marked by the mass migration and concentration of people in urban centers. Extensive observations substantiate an unbroken trajectory of escalating urbanization rates, showing no signs of reversal. Although occasional fluctuations may occur, the overarching trend is undeniably upward.

The case of Slovakia serves as a compelling illustration of this phenomenon. Research data [2] yields valuable insights into the unfolding dynamics of urban lifestyles, as outlined in Figure 1.

Place	1990	2014	2050 (forecast)
World	43%	54%	66%
Europe	70%	73%	82%
East Europe	68%	69%	78%
Slovakia	56%	54%	63%

Figure 1: World urbanism [2]

The expanding influence of urbanization has extensive repercussions on various facets of the climate crisis, establishing an intricate web of climatic effects. The progression of urban areas contributes significantly to the escalation of temperatures within cities, exacerbating the prevalent challenge of Urban Heat Islands (UHI). Moreover, it intensifies the local demand for heating and cooling, consequently resulting in a surge in greenhouse gas emissions. At present, the primary goal is to counteract this trajectory by curbing energy consumption. This article forms part of my dissertation research, which primarily seeks to identify strategies for reducing the dependence on additional energy for heating and cooling in our climate. While the complete elimination of this energy consumption may not be attainable, it is imperative to explore avenues for substantial reduction. Among the potential approaches, such as optimal architectural design, effective shielding, and suitable building envelopes, the utilization of passive heating and cooling elements emerges as a viable option. In my study, I specifically concentrate on the integration of vegetation elements and their influence on interior heating and cooling.

1.2 Vegetation elements

In the contemporary context, the myriad advantages of vegetation elements, particularly vegetation roofs, are indisputable. These elements offer a diverse array of benefits, encompassing the reduction of rainwater runoff, augmentation of urban biodiversity, mitigation of the urban heat island effect (UHI), improvement of air quality, moderation of temperature fluctuations on the roof surface to prolong the lifespan of the roof membrane, attenuation of noise levels, and a decrease in energy consumption. This article centers on delving into the impact of vegetation elements on energy consumption [1].

As temperatures soar both outdoors and indoors during the summer season, the demand for cooling escalates. In Slovakia, the recommended indoor temperature in winter is 20°C, while in summer, it is 26°C. Paradoxically, preferences often lean toward desiring a temperature of 20°C in summer and 24°C or higher in winter. Consequently, the demand for both heating and cooling rises. Since cooling is frequently achieved through air conditioning units, it contributes to elevated outdoor temperatures at both local and urban levels, exacerbating the UHI problem. Evapotranspiration, a process known for converting a substantial amount of solar radiation into latent heat that does not contribute to temperature rise [3], serves as an additional rationale for implementing passive cooling elements.

Why the emphasis on roofs? In our climate zone, maintaining vegetated exterior facades poses challenges. Moreover, horizontal building structures, such as roofs, undergo significant thermal stress during summer and require measures to prevent heat loss in winter [4]. Backed by proven benefits, several jurisdictions have opted to integrate vegetation elements into their cities and provide official support. Toronto, for instance, officially embraced this approach in 2009 [5], and other cities, including Chicago, have similarly demonstrated support for this initiative.

2 The Impact of Vegetative Roofs on Thermal Regulation in Buildings

Multiple factors contribute to the effectiveness of a vegetation roof in meeting a building's energy requirements. These factors include the substrate's thickness and thermal conductivity, volumetric humidity, vegetation height, leaf efficiency, emissivity, leaf coverage, stomatal resistance (which combines leaf water potential and solar flux), as well as the type and thickness of the roof insulation and local climate conditions [1]. Regarding the impact of vegetated roofs on heat flow and the thermal and technical parameters used in energy balances, relevant information was sourced from texts [4,6]. This particular case study focuses on the analysis conducted during the heating period. In the study [6], three roof types with varying insulation thicknesses were examined, emphasizing the importance of well-insulated roofs for our climate zone and country. This is only study, which can prove my concept to use in our well insulated roofs. Figure 2 presents the heat transfer coefficient values for these structures, both with and without a vegetated roof, considering three insulation levels [6].

1. uninsulated roof
    a. 25 cm concrete
    b. 10 cm concrete
2. slightly insulated roof
    a. 15 cm of concrete + 5 cm of insulation + 15 cm of concrete,
    b. 5 cm concrete + 5 cm insulation + 5 cm concrete
3. well-insulated roof
    a. 15 cm of concrete + 15 cm of insulation + 15 cm of concrete
    b. 10 cm of concrete + 10 cm of insulation + 10 cm of concrete

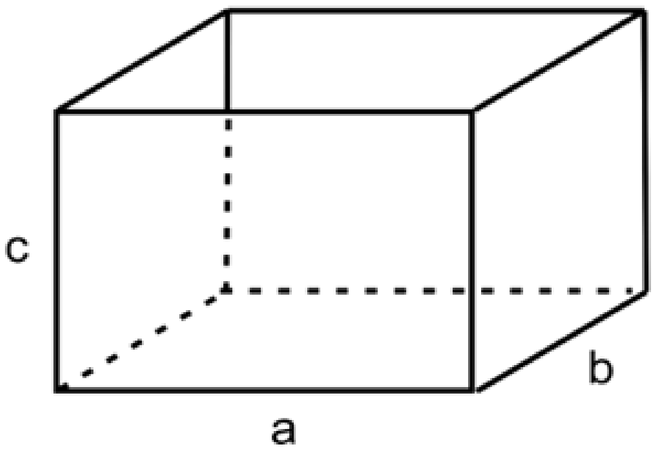
Type of roof		Heat conductivity coefficient ($W/m^2.K$)		Saving	
		Without vegetation	With vegetation	$W/m^2.K$	%
1	A	7,76	1,73	6,03	77,7
	B	18,18	1,99	16,19	89,1
2	A	0,74	0,55	0,19	25,7
	B	0,8	0,59	0,21	26,3
3	A	0,26	0,24	0,02	7,7
	B	0,4	0,34	0,06	15,0

Figure 2: Heat conductivity coefficient according to research [6]

3 Research focus and its procedure

The article introduces Case Study A, centered around an unconventional subject—an expansive warehouse-type hall measuring 100 x 200 x 10m (width x length x height), denoted as Part A1. In this instance, the roof area constitutes 43.48% of the entire heat exchange envelope of the structure. For the primary evaluation, Roof 3a, closely resembling our environmental conditions, was selected.
In the exploration of alternative objects or structures, it becomes pivotal to account for the building's configuration and the proportion between individual areas of the building's envelope and the vegetated region. This article underscores a structure characterized by a substantial roof-to-wall ratio. For comparative analysis, an apartment building measuring 14.76 x 31.66 x 23.1m (width x length x height), denoted as Part A2, was incorporated. In this case, the roof area constitutes a mere 15.13% of the total building area. Dimensions of the two objects for comparison are depicted in Figures 3 and 4.

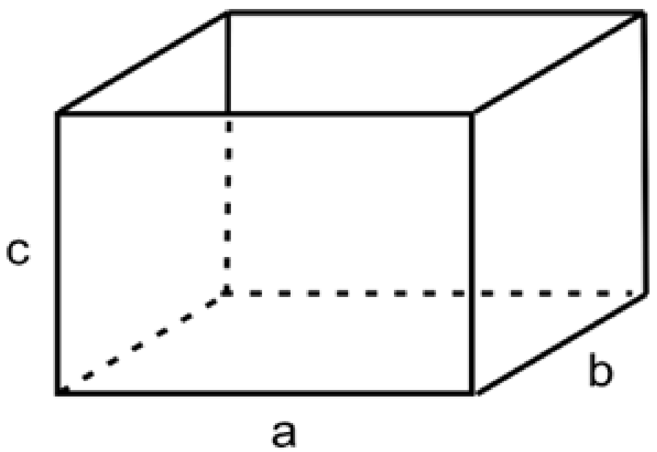
Object dimension



Dimensions		
Width (a)	100	m
Lenght (b)	200	m
Height (c)	10	m
Form factor		
V/A=	0,230	1/m

Figure 3: Dimensions of A1 object

Object dimension



Dimensions		
Width (a)	14,76	m
Lenght (b)	31,66	m
Height (c)	23,2	m
Form factor		
V/A=	0,285	1/m

Figure 4: Dimensions of A2 object

Following the selection of objects, a thorough comparison was conducted, focusing on the surfaces of the perimeter structures, encompassing the floor, walls, and roof. This analysis is graphically depicted in Figure 5 and Figure 6, offering a visual representation that distinctly illustrates the proportions and areas involved in the comparison.

The ratio of the area of the walls to the roof		
Area	m2	%
Walls	6000	13,04%
Roof	20000	**43,48%**
Object	46000	100,00%

Figure 5: Areas of A1 building envelope parts

The ratio of the area of the walls to the roof		
Area	m2	%
Walls	2153,888	69,74%
Roof	467,3016	**15,13%**
Object	3088,4912	100,00%

Figure 6: Areas of A2 building envelope parts

The thermal and technical parameters of the structures remain consistent across both parts, facilitating an accurate comparison limited to the roof structures. Part A1 is delineated in Figure 7 and Figure 8, offering a detailed showcase of the specific characteristics of the roof in this context. Correspondingly, Part A2 is visually represented in Figure 10 and Figure 11, providing insight into the distinctive features of the roof structure in that particular case.

Heat loss of an object without a vegetation element							
	A	U	θi	θe	Δθ	Qi	α
	m2	W/m2.K	°C	°C	K	W	%
SO1	6000	0,144	20	-13	33	28465,80	12%
PDL	20000	0,191	20	3	17	65022,56	27%
S - without vegetation	20000	0,222	20	-13	33	146779,52	61%
						240267,88	

Figure 7: Heat losses without a vegetated roof – Part A1. (SO1 – walls, PDL – floor and S – roof)

Heat loss of an object with a vegetation element							
	A	U	θi	θe	Δθ	Qi	α
	m2	W/m2.K	°C	°C	K	W	%
SO1	6000	0,144	20	-13	33	28465,80	12%
PDL	20000	0,191	20	3	17	65022,56	28%
S - with vegetation	20000	0,2053	20	-13	33	135477,50	59%
						228965,86	

Figure 8: Heat losses with a vegetated roof – Part A1. (SO1 – walls, PDL – floor and S – roof)

Part	S - without veg.	S - with veg	Saving	
	W	W	W	%
Construction	3429,52	3165,44	264,07	7,70%
Object	15167,46	14903,39	264,07	1,74%

Figure 9: A1 Object heat balance

Part A1 demonstrates a significant decrease in heat loss through the roof structure, supported by the available data. This impact is visually emphasized in the comprehensive energy balance of the object, as depicted in Figure 9. The energy balance of Part A is further detailed in Figure 12, offering a comprehensive overview of the energy flows and exchanges within the system.

Heat loss of an object without a vegetation element							
	A	U	θi	θe	Δθ	Qi	α
	m2	W/m2.K	°C	°C	K	W	%
SO1	2153,888	0,144	20	-13	33	10218,69	67%
PDL	467,3016	0,191	20	3	17	1519,26	10%
S - without vegetation	467,3016	0,222	20	-13	33	3429,52	23%
						15167,46	

Figure 10: Heat losses without a vegetated roof – Part A2. (SO1 – walls, PDL – floor and S – roof)

Heat loss of an object with a vegetation element							
	A	U	θi	θe	Δθ	Qi	α
	m2	W/m2.K	°C	°C	K	W	%
SO1	2153,888	0,144	20	-13	33	10218,69	69%
PDL	467,3016	0,191	20	3	17	1519,26	10%
S - with vegetation	467,3016	0,2053	20	-13	33	3165,44	21%
						14903,39	

Figure 11: Heat losses with a vegetated roof – Part A2. (SO1 – walls, PDL – floor and S – roof)

Part	S - without veg.	S - with veg	Saving	
	W	W	W	%
Construction	3429,52	3165,44	264,07	7,70%
Object	15167,46	14903,39	264,07	1,74%

Figure 12: A2 Object heat balance

Through extrapolating these values to the annual energy balance for heating, we can compute the corresponding savings in kWh/year or GJ/year. When these savings are amalgamated with current energy prices, it enables the determination of the total annual economic savings. Specifically for Part A1, these outcomes are outlined in Figure 13 to Figure 15. Similarly, for Part A2, the corresponding results are exhibited in Figure 16 to Figure 18, offering a comprehensive assessment of the economic benefits linked to the energy savings.

Data of the object:

Town:		Košice	
External calculated temperature:	t_e	-13	°C
Length of heating period:	d	223	days
Average temperature in the heating season:	t_{es}	2,9	°C
Average indoor temperature:	t_{is}	20	°C
Heat loss of the object:	Q_{HL}	240,2679	kW

Calculation of the expected heat demand for heating

d	D	ε	η_r	Q_{HL}	$Q_{ÚK/rok}$	
days	K.days	-	-	kW	kWh/rok	GJ/rok
223	3813,3	0,63	0,98	240,267883	428359,57	1542,09

Figure 13: Heating energy demand without vegetated roof and ventilation – Part A1

Data of the object:

Town:		Košice	
External calculated temperature:	t_e	-13	°C
Length of heating period:	d	223	days
Average temperature in the heating season:	t_{es}	2,9	°C
Average indoor temperature:	t_{is}	20	°C
Heat loss of the object:	Q_{HL}	228,9659	kW

Calculation of the expected heat demand for heating

d	D	ε	η_r	Q_{HL}	$Q_{ÚK/rok}$	
days	K.days	-	-	kW	kWh/rok	GJ/rok
223	3813,3	0,63	0,98	228,96586	408209,85	1469,56

Figure 14: Heating energy demand with vegetated roof and without ventilation – Part A1

The results of comparison					
	Heat energy demand		Cost comparison		
			Electricity	Gas	Heatpump
	kWh/rok	GJ/rok	€/rok	€/rok	€/rok
S - withou veg.	428359,567	1542,094	68537,53	26772,47	17134,38
S - with veg.	408209,850	1469,555	65313,58	25513,12	16328,39
Saving	20149,72	72,54	3223,95	1259,36	805,99
	4,704%				

Figure 15: A1 Object comparison of heat energy demand

Data of the object:

Town:		Košice	
External calculated temperature:	t_e	-13	°C
Length of heating period:	d	223	days
Average temperature in the heating season:	t_{es}	2,9	°C
Average indoor temperature:	t_{is}	20	°C
Heat loss of the object:	Q_{HL}	15,1675	kW

Calculation of the expected heat demand for heating

d	D	ε	η_r	Q_{HL}	$Q_{ÚK/rok}$	
days	K.days	-	-	kW	kWh/rok	GJ/rok
223	3813,3	0,63	0,98	15,1674648	27041,19	97,35

Figure 16: Heating energy demand without vegetated roof and ventilation – Part A2

Data of the object:

Town:		Košice	
External calculated temperature:	t_e	-13	°C
Length of heating period:	d	223	days
Average temperature in the heating season:	t_{es}	2,9	°C
Average indoor temperature:	t_{is}	20	°C
Heat loss of the object:	Q_{HL}	14,9034	kW

Calculation of the expected heat demand for heating

d	D	ε	η_r	Q_{HL}	$Q_{ÚK/rok}$	
days	K.days	-	-	kW	kWh/rok	GJ/rok
223	3813,3	0,63	0,98	14,9033921	26570,39	95,65

Figure 14: Heating energy demand with vegetated roof and without ventilation – Part A2

The results of comparison					
	Heat energy demand		Cost comparison		
			Electricity	Gas	Heatpump
	kWh/rok	GJ/rok	€/rok	€/rok	€/rok
S - withou veg.	27041,187	97,348	4326,59	1690,07	1081,65
S - with veg.	26570,387	95,653	4251,26	1660,65	1062,82
Saving	470,80	1,69	75,33	29,42	18,83
	1,741%				

Figure 15: A2 Object comparison of heat energy demand

Table 1 furnishes a thorough comparison between Part A1 and Part A2, emphasizing the percentage savings realized with a vegetated roof, while considering the distinct ratios of roof area. It becomes apparent that the adoption of a vegetated roof offers stronger justification, especially concerning heating, for structures with larger horizontal construction areas in contrast to vertical ones. The table offers a lucid summary of the energy savings, highlighting the advantages associated with incorporating a vegetated roof in such scenarios.

Table 1: Final comparison of construction with and without vegetation

Roof	Area ratio roof/object	Heating energy demand		Savings	
		Without VR	With VR		
		MWh/a	MWh/a	MWh/a	%

A1	43,48%	428,36	408,21	20,15	4,71%
A2	15,13%	27,04	2,66	0,47	1,74%

4 Conclusion

The overall impact of the vegetation roof on the structure is contingent upon several factors, with the findings affirming its influence on heating. Simultaneously, a secondary comparison based on the ratio substantiated its suitability across various area ratios. It's important to note that the focus of this article does not adhere to economic principles, as the objective isn't a singular comparison of an indicator and its financial implications. Instead, the article aims to broaden the perspective on vegetated roofs and complement their advantages.

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References

[1] Susca, T. (2019). Green roofs to reduce building energy use? A review on key structural factors of green roofs and their effects on urban climate. Energy and Buildings.

[2] United Nations. (2014). World Urbanization Prospects: The 2014 Revision, Highlights. Retrieved from https://population.un.org/wup/Publications/Files/WUP2014-Highlights.pdf

[3] World Bank. (2021). Urban population (% of total population). Retrieved from https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS?end=2021&name_desc=false&start=1960&view=chart

[4] Takakura, T., Kitade, S., & Goto, E. (2002). Cooling effect of greenery coverover a building. Energy and Buildings.

[5] Theodosiou, T. G. (2003). Summer period analysis of the performance of a planted roof as a passive cooling technique. Energy and Buildings.

[6] City of Toronto. (2009). Green Roof Bylaw. Retrieved from https://www.toronto.ca/legdocs/bylaws/2009/law0583.pdf

[7] Niachou, A., Papakonstantinou, K., Santamouris, M., Tsangrassoulis, A., & Mihalakakou, G. (2001). Analysis of the green roof thermal properties and investigation of its energy performance. Energy and Buildings.